# Final technique Report

# Dynamics of Optical Recombination in GaN and $Al_xGa_{1-x}N$

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Hongxing Jiang (P.I.)
Department of Physics
Kansas State University
Manhattan, KS 66506-2601
Tel: (785)532-1627
Fax: (785)532-5636 (or 532-6806)
E-mail: jiang@Phys.ksu.edu

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13. ABSTRACT *(Maximum 200 words)*

During the project period, we have investigated the optical properties of III-nitride heterostructures and quantum wells and provided input for the improvement of materials quality, understanding of impurity properties, and optimization of device design. We were the first group to observe the persistent photoconductivity (PPC) effect in p-type GaN epilayers and in AlGaN/GaN heterostructures and utilized PPC effect to study the impurity properties in these materials. We were also one of the first few research groups to employ picosecond time-resolved photoluminescence (PL) measurement technique to study mechanisms of optical transitions, LED emission, and lasing in GaN and related materials.

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III-nitride wide bandgap semiconductors (GaN, InGaN, AlGaN) have been recognized as a technologically important materials system due to their applications for optical devices which are active in the blue and ultraviolet (UV) wavelength regions and electronic devices which are capable of operation at high temperature, high power, and harsh environments. *The objective of our ARO supported research is to investigate the optical transitions and their dynamic processes in different III-nitride device structures and to provide input for developing suitable material quality and device design.* During the project period, we have investigated the optical properties of III-nitride heterostructures and quantum wells and provided input for the improvement of materials quality, understanding of impurity properties, and optimization of device design. We were the first group to observe the persistent photoconductivity (PPC) effect in p-type GaN epilayers and in AlGaN/GaN heterostructures and utilized PPC effect to study the impurity properties in these materials. We were also one of the first few research groups to employ picosecond time-resolved photoluminescence (PL) measurement technique to study mechanisms of optical transitions, LED emission, and lasing in GaN and related materials. Here we give a brief account of our accomplishments during the period of support. More details can be found in the publications listed [1-63] in part h) below.

a. <u>Fundamental Optical Transitions in GaN Epilayers</u>[1-16, 22,34, 44,45,53]

We have employed picosecond time-resolved PL to study the dynamics of optical transitions in GaN (including n-type, p-type, and intrinsic) and InGaN epilayers, GaN/AlGaN and InGaN/GaN MQWs grown by MBE and MOCVD. Our studies of dynamics of optical transitions have not only identified mechanisms of various optical transitions in different structures, but also provided valuable information for the improvements of materials quality and device structures. From these studies, we have obtained a fairly complete picture for the band structure near the $\Gamma$ point and the associated fundamental optical transitions in GaN epilayers. The electron and hole effective masses, free- and bound-exciton binding energies, exciton recombination lifetimes have been obtained. Our results have demonstrated that time-resolved PL is a powerful method for determining sample crystalline quality, purity, alloy composition, and QW interface properties.

b. <u>Optical Properties of Quantum Well Structures</u> [16,19,21,26-28,31,33,43,62]

Effects of well thickness and Si doping on the electronic properties of GaN/AlGaN and InGaN/GaN MQWs have been investigated. Our results have yielded that (i) with respect to the GaN epilayers, the low temperature excitonic transition peaks in continuous wave (cw) spectra in nominally undoped MQWs were blue shifted in MQWs with well thickness $L_W < 25$ Å due to quantum confinement, but were red shifted in MQWs with well thickness $L_W$ in between 30 Å and 40 Å due to the effect of piezoelectric field induced by lattice mismatch-induced stain, (ii) the exciton recombination lifetimes in MQWs of narrow well thickness increased linearly with temperature up to 60 K (a hallmark of radiative recombination in MQWs), (iii) impurity related transitions have a strong influence on the emission properties of undoped MQWs of large well thickness ($L_W > 50$ Å), and iv) Si-doping improved significantly the quality of MQWs of large well thickness' ($L_W > 50$ Å).

c. <u>Effects of Injection Carriers on Refractive Index</u> [17,39,46]

An important experimental observation in pulsed or less superior InGaN laser diodes (LDs) was that the measured mode spacing of the lasing spectra could be one order of magnitude larger than the value "calculated" from the known cavity length. We have re-derived an accurate formula for describing the mode spacing in InGaN LDs and shown that the discrepancy between the "expected" and observed mode spacing is due to the effect of carrier induced reduction of the refractive index under lasing conditions and this discrepancy decreases as the threshold carrier density required for lasing decreases. Since the carrier induced reduction of the refractive index is expected only from an electron-hole plasma state, our analysis supported that the lasing mechanism in InGaN LDs is conventional, i.e., electron-hole plasma recombination provided the optical gain. We have also studied the properties of surface emission of an InGaN/GaN heterostructure by optical pumping. Under strong optical excitation, the emission energy was blue shifted with an increase of pumping intensity and the emission band switched from one dominating emission line to two separate emission lines.

These results can also be accounted for by the reduction of refractive index due to the formation of an electron-hole plasma state under strong optical excitation.

d. Impurity Properties in III-Nitrides [7,8,14,23,25,29,36,41]

We have observed persistent photoconductivity (PPC) effect in p-type GaN epilayers grown by MOCVD and reactive MBE as well as in a two dimensional electron gas (2DEG) systems formed by an AlGaN/GaN heterostructure. The manifestation of PPC has been used to probe the nature of impurities in p-type GaN. This work has stimulated many theoretical and experimental investigations aiming at the understanding of the impurity properties and PPC in GaN. We have also utilized unique features of PPC to study the properties of 2DEG formed by the AlGaN/GaN heterostructure. An electronic transition from the first to the second sub-band in the 2DEG channel has been observed by monitoring the 2DEG carrier mobility as a function of carrier concentration through the use of PPC. A significant 2DEG mobility enhancement has been observed in the PPC state. These results are expected to have implications on field effect transistor (FET) applications based on the GaN system.

e. Fabrication and Optical Studies of III-Nitride microstructures and devices [30,32,35,47,55-57,63]

We have fabricated III-nitride microdisks by dry etching from GaN/AlGaN and InGaN/GaN MQW structures. The optical properties of these microdisks have been studied. With respect to the original MQWs, the intrinsic transitions from both the wells and barriers exhibited an approximate 10-fold increase in both recombination lifetime and quantum efficiency upon formation of microdisks. Our preliminary results imply a bright future for III-nitride micro-size optoelectronic devices, including micro-LED's, micro-LED arrays, microcavity lasers, and vertical cavity surface emitting lasers (VCSELs). The optical properties of a GaN pyramid array fabricated by selective overgrowth have also been studied. GaN p-n junction microdisk LEDs have been fabricated and studied.

f. Characterization of InGaN/GaN MQWs[38]

$In_xGa_{1-x}N$/GaN MQW system is distinctively different from the better understood MQW systems such as GaAs/AlGaAs because the wells are formed by an alloy material. In additional to the well known effect of interface roughness in MQWs, alloy fluctuation in InGaN wells is also expected to have a strong influence on their optical properties. Knowledge concerning the interface roughness and alloy fluctuation in the InGaN/GaN MQW system is important for the improvement of the materials quality as well as to the device design. However, when both types of disorders are simultaneously present in the same system, a direct method for determining these parameters do not currently exist. Most recently, we have developed a method for determining the alloy fluctuation parameter and interface roughness parameter in $In_xGa_{1-x}N$/GaN MQWs, which can be applied to other MQW systems in which wells are formed by alloy materials. The method is based on fitting the low temperature PL emission spectra to a formula derived by our group.

g. Materials Growth by MOCVD [38,44]

We have made rapid progress in GaN materials growth by MOCVD. Typical as-grown GaN films produced by our MOCVD system emit only the intrinsic free-exciton transitions and exhibit the room temperature electron concentration of $5 \times 10^{16}$ $cm^{-3}$ and mobility of 550 $cm^2/Vs$. They can be doped n-type with Si and p-type with Mg. We have also fabricated the first GaN n-i-p-i superlattice in our MOCVD system, which is designed for the studies of Si and Mg impurity properties and their associated optical properties in GaN. We are working toward further improvements in p-type doping by Mg and the growth of AlGaN alloys and GaN/AlGaN QWs.

h. List of Publications Related to ARO Award

We have disseminated our research results through publications in scientific journals. We have published a number of papers on III-nitride related materials since 1995 (papers marked with * sign have acknowledged ARO support):

1. A. S. Dissanayake, J. Y. Lin, H. X. Jiang, Z. J. Yu, and J. H. Edgar, "Low Temperature

MOCVD Epitaxial Growth and Photoluminescence Characterization of GaN", Appl. Phys. Lett. 65, 2317 (1994).

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i. Technology Transfer

We are collaborating very closely with several nitride material growth and device fabrication groups in the country, including Prof. Hadis Morkoc of Virginia Commonwealth University, Prof. M. Asif Khan of University of South Carolina, Dr. W. Yang of Honeywell Technology Center, Dr. G. Sullivan of Rockwell Science Center, and Prof. James Edgar of Kansas State University. Information obtained from our studies have been provided to these groups for the further development of suitable material quality and device structures.